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I, JANENE PEISKER, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2003900272 for a patent by HYBRID ELECTRONICS AUSTRALIA PTY. LTD. as filed on 20 January 2003.

WITNESS my hand this
Seventh day of November 2003

JANENE PEISKER
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PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED:

THICK-FILM CIRCUITS INCLUDING A TITANIUM SUBSTRATE

This invention is described in the following statement:

THICK-FILM CIRCUITS INCLUDING A TITANIUM SUBSTRATE

The present invention relates to electronic circuits. In particular the invention relates to electronic circuits including thick-film hybrid circuits that are constructed on or include a metal substrate.

The present invention is related to provisional patent application 2002952359 filed 30 October 2002, the disclosure of which is incorporated herein by cross-reference.

It is known that electronic circuits and sub-assemblies can be manufactured using thick-film hybrid-circuit technology. The substrate, or base, for the circuit is typically a flat, rigid sheet of electrically-insulating material, such as ceramic, e.g. alumina. Resistors and interconnecting conductors or tracks are printed onto the substrate, typically by screen printing with special inks, pastes or compositions, which are then fused by firing at a high-temperature. Insulating layers, of materials such as glass, are similarly printed and fired, either to separate different layers of conductors, or to make dielectric layers for capacitors. Semiconductor devices, such as transistors, diodes and integrated circuits, and passive electronic components may be attached to the conductive tracks to provide further electronic functions. A combination of printed thick-film components and semiconductor devices makes up a complete structure encompassed by the term "hybrid circuit". The fired inks or compositions make up the "thick film" referred to in the phrase "thick-film hybrid circuit".

In hybrid-circuit manufacture generally, thermal-expansion properties of various materials used to construct the circuit should be relatively similar. When a layer of ink is printed onto a substrate and fired, and the thermal coefficient of expansion (TCE) of the fired ink differs substantially from that of the substrate, the whole circuit may be subjected to bending forces as its temperature changes. This may cause noticeable curvature in the finished product. Bending may also be sufficient to interfere with the process of printing further layers of ink or dielectric material after the first layer has been printed and fired. Even in cases where visible bending is not apparent, stresses set up by temperature changes may cause cracking in glass layers, or changes in the resistance values of thick-film resistors.

In order to avoid producing bending stresses in fired hybrid circuits, manufacturers of inks and insulating compositions provide materials that are tailored to match as near as possible the thermal properties of typical substrate material, e.g. a ceramic such as 96% alumina.

One virtue of conventional hybrid circuit technology is that the thermal conductivity of an alumina substrate is relatively high (about 26 $W.m^{-1}K^{-1}$), compared with common printed-circuit board materials, such as epoxy-glass laminates (about 0.3 $W.m^{-1}K^{-1}$). High thermal conductivity is desirable because it assists the hybrid circuit to dissipate heat generated by circuit elements mounted on the substrate.

The prior art includes use of a metallic substrate material, such as stainless steel, which can be coated with one or more insulating layers to form the base

on which resistive or conductive elements are printed. Different grades of stainless steel have different proportions of alloying elements, and consequently differ in their TCEs, thermal conductivities and other properties. Manufacturers of inks and insulating compositions provide a comprehensive range of materials that are tailored for ceramics such as alumina, but provide a relatively limited range of materials (e.g. inks) that are tailored for particular grades of stainless steel, for example AISI (American Iron and Steel Institute) grade 430 which has a thermal conductivity comparable with that of alumina. Stainless steels generally have relatively high TCEs compared with alumina and typical insulating compositions that may be used with it. For example, while alumina has a TCE of 6.4×10^{-6} K^{-1}, AISI grade 430 stainless steel has a TCE of 10.4×10^{-6} K^{-1}; and AISI grade 316L, which has better corrosion resistance, has a TCE of 15.9×10^{-6} K^{-1}.

The extent of bending, that results from a given temperature rise and given disparities in TCEs of the various layers, also depends on the thickness of the layers and the moduli of elasticity of the materials used therein. In some hybrid-circuit applications, such as a pressure transducer, the thickness of the substrate layer is important because the substrate is also a diaphragm, and is subject to additional bending under influence of differential pressure that is to be measured. In high-pressure measurement, the ultimate yield strength of the material may set a minimum thickness for the substrate. In other hybrid-circuit applications, such as a temperature-transducer or calorimetric flow-transducer, the thickness of the substrate layer may be important because thermal resistance through the substrate, transversely or radially, is an integral factor in

the operation of such a transducer. In these cases, thermal conductivity of the substrate material may also be important.

Due to the relatively high TCEs associated with stainless steels, the range of insulating compositions and inks that can be used on stainless steel substrates is limited. A manufacturer of a hybrid-circuit is therefore constrained, both in terms of the grade of stainless steel that can be used, and in the range of materials available for coating and printing on stainless steel substrates. The present invention may provide an alternative metal-substrate technology that more closely matches the properties of the well-established ceramic substrate technology.

The present invention provides an electronic circuit such as a thick film hybrid circuit that includes or is constructed upon a titanium metal or titanium alloy substrate. The substrate may be coated with one of more layers of fired insulating composition, to form the base upon which conductive or resistive inks and further insulating layers may be printed to produce the thick-film hybrid circuit. Throughout the description, the term "titanium" is to be interpreted as including titanium-based alloys.

The present invention may remove at least some of the restrictions on the types of pastes or compositions from which insulating layers, conducting tracks or resistive elements are formed when stainless-steel substrates are used. Furthermore, the range of available grades of titanium and its alloys when compared to prior art substrate materials allow the properties of a substrate to be tailored to suit particular applications, such as pressure or flow transducers.

The present invention may utilize the relatively wide range of properties available in both commercially pure titanium and titanium-based alloys, so that a more optimum combination of physical properties can be chosen for a particular application.

Preferred forms of the invention may provide hybrid circuits for transducers used to sense temperature, fluid flow, strain or pressure, but are not restricted to such applications. Such transducers may use the metal substrate in a dual role. Firstly, the substrate may constitute a diaphragm whose mechanical and/or thermal properties may play an integral part in sensing a measured quantity. Secondly, the substrate may constitute a base for printing electronic circuits used to amplify or process the electrical signals generated in the transducer, or other circuits associated with the transducer application.

The use of a substrate material such as titanium or titanium alloy may at least improve the match between the thermal coefficient of expansion (TCE) of the substrate and elements or materials used to manufacture the circuit, for example commercially available hybrid circuit inks for ceramic substrates such as Metech 3504 (Silver Palladium conductor), Tanaka TR-4920 (Silver Palladium conductor), ESL 9695 (Silver Palladium conductor), resistor compositions such as Metech 9100D and insulating compositions such as Metech 7600A. Such commercially available inks may be used with titanium or titanium alloy substrates due to the relatively closely matching properties of titanium when compared with ceramics.

An improved match between the TCEs of the substrate and other elements of the circuit may reduce the bending and stress-magnitudes of a completed thick-film hybrid circuit formed on a metal substrate. With a suitably-chosen grade of titanium, the TCE of the metal is closer to that of alumina than is the TCE of stainless steel grade 430. A numerical comparison is given in Table 1, fourth column. This means that, for many purposes, inks and dielectric materials that would be used commercially on ceramic substrates can be printed on an insulation-coated titanium substrate, without producing as much thermal bending stress as would result from using the same materials on stainless steel of comparable thickness. This may be important, not only because the mechanical effect of bending, but also because the surface strain associated with bending affects the resistance and stability of resistive materials printed and fired on the substrate. Due to the greater range of commercially available inks and dielectric materials for use on ceramic substrates, use of a titanium or titanium alloy substrate (which more closely matches properties of a ceramic substrate) may also reduce temperature dependence of resistors printed and fired on such a substrate.

Table 1

Material	Minimum yield strength, 0.2%, MPa	Modulus of Elasticity, Gpa	Coefficient of thermal expansion, $°K^{-1}$ (TCE)	Thermal Conductivity, $W.m^{-1}.K^{-1}$ @ 100°C	Electrical resistivity, $\Omega.m$
Stainless steel 430	205	200	10.4×10^{-6}	23.9	0.60×10^{-6}
Stainless steel 316L	170	193	15.9×10^{-6}	16.3	0.74×10^{-6}
Titanium Grade 3	380	105 to 120	8.6×10^{-6}	21.79	0.54×10^{-6}
Titanium Grade 4	483	105 to 120	8.6×10^{-6}	16.95	0.60×10^{-6}
Titanium	825	107 to 122	9.0×10^{-6}	6.6	1.68×10^{-6}

Grade 5					
Alumina 96%			6.4×10^{-6}	26	

A further benefit of the use of a titanium or titanium alloy substrate material is that, by choosing an appropriate grade of titanium, the ratio of yield strength to modulus of elasticity can be much higher than for stainless steel. Table 1 compares two grades of stainless steel with two grades of titanium, based on AISI and as ASTM (American Society for Testing and Materials) specifications. In applications such as pressure transducers, the relatively high yield strength of these grades of titanium allows thinner diaphragms to be used without performance degradation or diaphragm failure due to yield. Pressure transducers generally operate on the principle of detecting strain at the surface of a diaphragm, using the change of resistance of one or more strain gauges, or using piezo-electric strain sensing. Reducing the diaphragm thickness increases the degree of surface strain associated with bending under a given pressure, and reducing the modulus of elasticity further increases the surface strain for a given pressure. The sensitivity of a pressure transducer based on an insulated metal-diaphragm thick-film hybrid circuit, using titanium or titanium alloy as the substrate material may therefore be enhanced.

A further benefit of the use of a titanium or titanium alloy substrate material is that it may be highly resistant to corrosion in a wide range of environments. As mentioned earlier, when stainless steel is used as a hybrid-circuit substrate, grade 430 is preferred because its low TCE can be matched with insulating compositions and resistive and conducting inks. Grade 316L is more desirable from a corrosion point of view, but its TCE is 50% higher, and its thermal conductivity is 2/3 that of 430. A good dielectric thermal match with 316L is not

currently available. Replacing the stainless steel with titanium grade 3, good corrosion resistance can be combined with a lower TCE and almost the same thermal conductivity as grade 430 stainless steel. The corrosion-resistance of a transducer based on an insulated metal-diaphragm thick-film hybrid circuit, may therefore be enhanced by using titanium or titanium alloy as the substrate material.

A further benefit of the use of a titanium or titanium alloy substrate material is that it may avoid diffusion of iron contamination, from the metal substrate into the main insulating layer(s) of a thick film hybrid circuit on to which circuit elements are printed. Diffusion of iron from a steel or stainless steel substrate, during firing of the insulating layer, tends to degrade the breakdown voltage of the insulating layer. This may be minimized by the use of additional insulating layers, or by the use of a protective noble-metal layer under the insulating layer. Both these methods require additional manufacturing steps, compared with the present invention.

A further benefit of the use of a titanium or titanium alloy substrate material is that the wide range of properties available in different grades of titanium (both commercially pure grades and alloys) may allow thermal and mechanical properties of the metal substrate to be tailored to satisfy particular requirements arising in a wide range of potential applications of metal-substrate based thick-film hybrid technology, including but not restricted to, particular requirements of transducers based on metal-substrate thick-film hybrid technology, used to measure temperature, fluid flow, differential pressure and mechanical strain.

Examples of Typical Customer Requirements and Titanium Optimisation are set forth below:

Customer 1 (pump sensor) requires

- High thermal conductivity for triac heat sinking into water
- High strength for high pressure water
- Low Young's modulus for pressure measurement sensitivity
- No bending during manufacture

In these circumstances it is desirable to choose Titanium Grade 3

Customer 2 (battery operated flow sensor) requires

- Low thermal conductivity for minimum heat loss
- Minimum thickness for lowest power and fast response
- High strength for water pressure specification

In these circumstances it is desirable to choose Titanium Grade 5

A further benefit of the use of a titanium or titanium alloy substrate material is that presently-available resistive inks are suitable for use on top of the insulating layers that are compatible with the titanium substrate. Presently available resistive inks are not suitable for use on top of the insulating layers formulated for stainless steel substrates. It has been proposed that a special interface dielectric be used as an intermediate layer between the stainless-steel insulating layer and the resistive inks (US Patent 6233817), but this requires additional processing during manufacture.

Finally, it is to be understood that various alterations, modifications and/or additions may be introduced into the constructions and arrangements of parts previously described without departing from the spirit or ambit of the invention.

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